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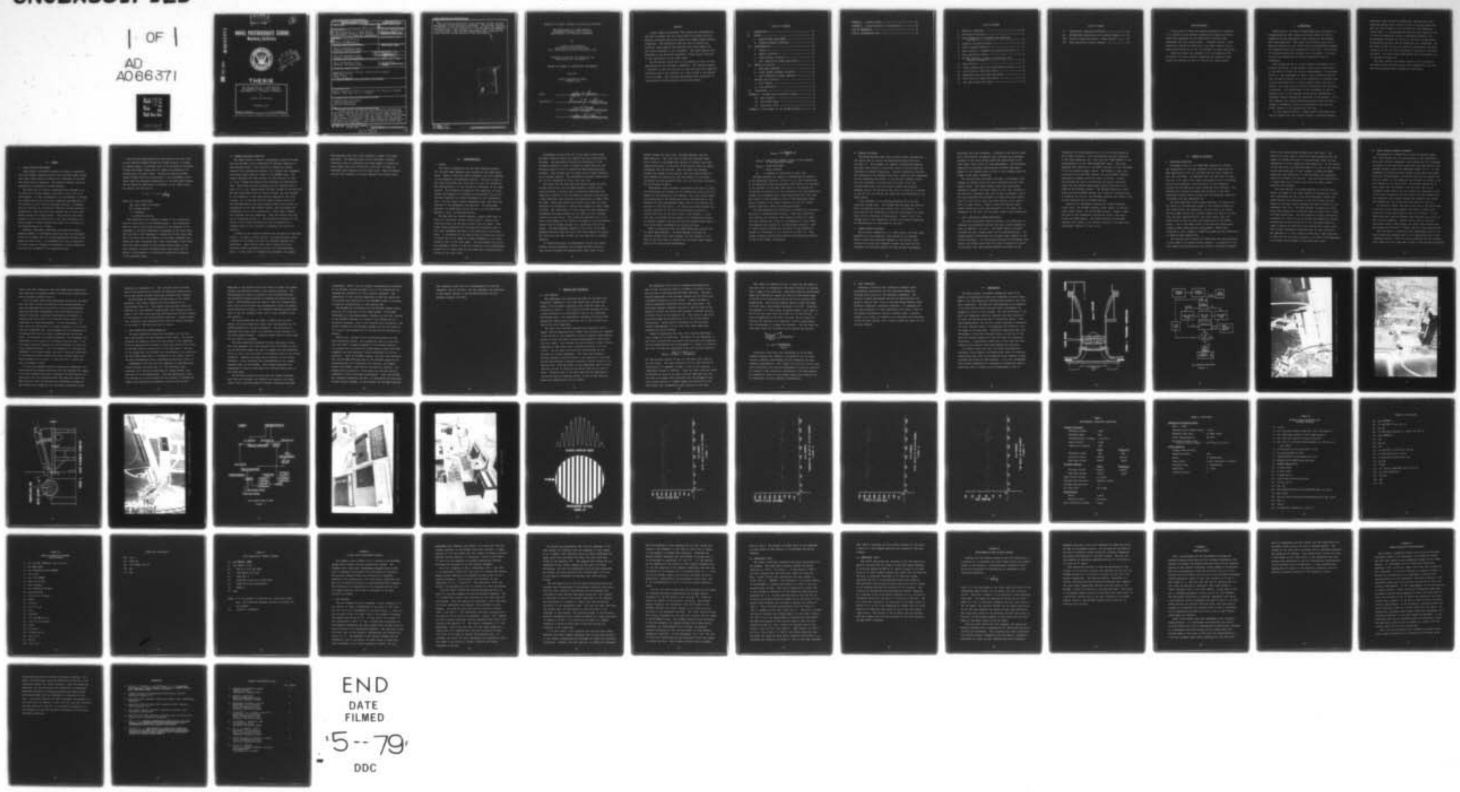

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THESIS

THE APPLICATION OF A LASER DOPPLER VELOCIMETRY SYSTEM TO FLOW VELOCITY MEASUREMENTS IN A TRANSONIC COMPRESSOR

by

Jeffrey Alan Harrison

December 1978

Thesis Advisor: D. J. Collins

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The Application of a Laser Doppler Velocimetry System to Flow Velocity Measurements in a Transonic Compressor

by

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Lieutenant, United States Navy
B.S., North Carolina State University, 1972

Submitted in partial fulfillment of the requirements for the degree of

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December 1978

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ABSTRACT

A laser doppler velocimeter (LDV) system was developed and utilized to measure the flow velocities in the axial and tangential directions behind the rotors of a single stage transonic compressor. The backscatter mode was used to acquire the scattered light signals from particles that were seeded into the airflow upstream of the compressor. The light signals were generated as the particles traversed a fringe pattern produced by the intersection of two laser beams.

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I. INTRODUCTION

Traditionally, the task of determining flow velocities in turbomachines has been reserved for metal probes of finite dimensions placed physically in the vicinity of the required flow characteristics. The actual flow velocity could not be measured directly but was deduced from the relationship between the stagnation and static properties of the flow. The accuracy of the measurements was dependent upon the degree of accuracy at which the stagnation and static properties could be determined.

Even though the use of a laser doppler velocimeter is not without inaccuracy, it has become a useful and accurate tool in the field of fluid flow velocity measurements. As discussed in Ref. 1, the advantages of using a laser doppler system are that the method results in no flow disturbance or pressure loss as would be present with a metal pressure probe, and that it offers a very high accuracy without the necessity for extensive calibration. One disadvantage of this procedure is that an optical access to the internal volume of the turbomachine is necessary without limiting the operation of the machine. It is also required that light-scattering particles that are small enough to dependably follow the streamlines of the flow be either present in or injected into the flow.

In this research effort, a laser doppler velocimeter was used to measure the flow velocity behind a rotating transonic

compressor rotor section by seeding the upstream flow with particles smaller than a micron in such a way that they would exit the rotor section in the vicinity of a LDV measuring volume (Fig. 1). By counting the time that each particle took to cross the measuring volume's interference pattern, the instantaneous velocity at a point in the flow was determined. By measuring the axial and the tangential flow components, the yaw angle of the flow was calculated by determining the angle formed by the two velocity components as compared to the axial direction. Any pitch angle measurements were unobtainable due to equipment limitations.

The laser doppler velocimeter proved to be an effective instrument which produced results that compared with the data that had previously been obtained by other means.

II. THEORY

A. LASER DOPPLER VELOCIMETRY

Laser doppler velocimetry derives its basis of operation from the doppler frequency shift of the scattered light caused when laser light comes in contact with a particle in the flow with some velocity component. The doppler frequency shift is measured by an electronic counter directly.

The laser and its optical accessories were arranged so as to focus the two laser beams on the point in the flow to be investigated. At this intersection, it is necessary to arrange the fringe pattern such that each fringe was perpendicular to the direction of the velocity component desired. To measure the flow velocity in a particular direction, either axially or tangentially, particles that were smaller than a micron were passed through the fringe pattern. The particles were small enough to follow the streamlines of the flow accurately, but large enough to scatter enough laser light to be acquired by the photomultiplier as a signal.

Normally, high speed compressed flow does not contain adequate numbers of contaminant particles that have diameters which are no larger than the fringe spacing and provide a good signal-to-noise ratio. To accomodate this lack of particles, a process known as "seeding" was employed to inject particles into the flow upstream of the measuring volume.

The velocity measurements were made based on the fact that as each particle passed through the fringe pattern, it caused an optical signal of scattered light to be produced as it passed through the bright fringe while no signal was produced as it traveled past the dark fringe. Knowing the spacing between bright fringes which was proportional to the wavelength of the laser light and inversely proportional to the half-angle between the two beams and measuring the frequency of the light signal, one obtains the velocity by:

$$V = D_f \cdot f \; ; \; D_f = \frac{\lambda}{2\sin(\frac{\theta}{2})}$$

where λ = laser wavelength

$\frac{\theta}{2}$ = laser beams' half-angle

D_f = fringe spacing

f = frequency

V = particle velocity

The backscatter lens focuses an image of the intersection point or focal point on the photomultiplier. The backscatter mode was used in this study due mainly to the presence of the compressor's hub which prevented the passage of the laser beams from one side of the compressor's casing wall to the other side. Due to the fact that the intensity of the light scattered back toward the laser transducer was a small percentage of that which would have been received in the forward scatter mode, it was also necessary to use an increased laser power level and to employ a beam expander to effectively increase the intensity of the scattered light.

B. COUNTER PROCESSOR OPERATION

The 55L90 Counter Processor incorporated various functions with its 250 MHZ clock to determine the doppler frequency of the scattered light. Once a particle crossed the initial fringe of the interference pattern, two counters were triggered, each being timed using the output of the 250MHZ clock. One counter measured the time interval for the particle to cross 5, or N_L, fringes and halted while retaining its time measurement. The second counter continued with its counting until a total of 8, or N_H, fringe spaces had been crossed by the particle. The time measurement from the second counter, T_H, was compared in the comparator to the time interval measured by the first counter, T_L, if the time from the second counter was 8/5 of the time measured by the first counter within the accuracy, E, established by the COMP ACCURACY switch, then the signal was considered to be a valid reading and a "data ready" command was outputted from the comparator. This LDV counter principle can be visualized in Fig. 2. The equivalent frequency was the output of the counter processor and was transferred to a computer where it was processed to determine the particle's velocity.

Included in the counter processor were low-pass and high-pass filters. By means of these filters, the high frequency noise component of the signal and the low frequency pedestal were eliminated. These filters were used in conjunction with threshold window adjustments which set the upper amplitude limit. If this limit or threshold was exceeded, the signals

were rejected since this would represent a signal from large particles. The amplifier gain control performed a similar function in that it attenuated the input signal to reduce the noise signal below the 50 millivolt level and to bring the scattered light signals above the same level. These validation circuits were required to provide adequate and reliable data.

III. INSTRUMENTATION

A. OPTICS

The optics requirements for the laser apparatus except for the 55L77 Beam Expander were provided by the 55L88 Transducer. Figure 3 shows the laser transducer with beam expander in its alignment and operating position. The small window in the right end permits the laser beam to enter the transducer. The photomultiplier is the cylindrical attachment on its upper surface. The transducer housing has the capability of being rotated 360 degrees to accomodate the measurement of any flow velocity component in a plane orthogonal to the transducer's axis. For the single channel backscatter mode, the following sections of the transducer were employed: the 55L84 Beam Splitter, the 55L86 Back Scatter Section, and the 55L87 Beam Separator, Lens, and Mounting Section.

The Beam Splitter Section permits a single laser beam to enter the transducer through a small window. Using a beam splitting prism, the one beam is split into two beams. Additional prisms separated the two beams and redirected them so that they propagated parallel to the centerline of the transducer. An adjustment on the beam splitter provided the ability to adjust one of the beams in a plane orthogonal to the plane formed by both of the laser beams. This adjustment was used in the alignment process to check the formation of the interference pattern and to insure that the two beams were intersecting one another at the focal point.

Adjustments on the front end of the laser optical bench provided a means by which the optimal beam spot intensity was achieved. The adjustments altered the orientation of the transducer chassis in order to align the input beam with the entrance window so that it entered the beam-splitting prism properly. This insured that the beams were of equal intensity and of optimal quality. The adjustments provided limited movement of the transducer in pitch, yaw, and roll.

The beams from the Beam Splitter passed through the Backscatter Section and into the Beam Separator Section which contained pairs of mirrors that by selection determined the separation distance of the two beams as they exit this section. A beam separation knob provided beam separations of 20mm, 40mm, and 80mm. There were three focal lenses which gave the laser apparatus the capability of using focal lengths of 120mm, 300mm, or 600mm. The combination of focal length and beam separation determined the angle between the two beams as they converged towards the focal point. This angle was important due to its direct relationship to the number of fringes in the interference pattern and the fringe spacing for a particular laser wavelength. The Beam Expander attached to the front of the Beam Separator Section where the focal lens would usually be placed. The focal lens was then screwed into the open end of the Beam Expander.

As stated previously, the Backscatter Section was placed between the Beam Separator and the Beam Splitter Sections. This section accepted the backscattered light after it had

passed through the focal lens, the Beam Expander, and the Beam Separator. The focal lens focused the scattered light onto a mirror in the Backscatter Section to reflect the light towards the pinhole in the side of the section where the photomultiplier tube was secured. When the light was properly focused and aligned on the pinhole, the only light allowed to pass through the pinhole and into the aperture of the photomultiplier was the scattered light from the particles traversing the interference pattern.

Using metric Allen wrenches, adjustments were made to refine the positioning and focusing of the backscatter focal point with respect to the position of the pinhole. Two Allen screws affect the positioning of the backscatter mirror perpendicular to the direction of the backscattered light; this in turn affects the position of the focal point. One other Allen screw adjusts the vertical position of the pinhole providing the ability to correct the focus of the focal point at the pinhole. A side view port is provided in the casing of the Backscatter Section to provide viewing of the pinhole and the backscattered light's focal point while adjustments are being performed.

Used in conjunction with the 55L86 Backscatter Section was the 55L77 Beam Expander. The Beam Expander utilized the relation between beam waist diameter and the diameter of the beam at the focal lens to optimize the scattered light signals derived from backscatter measurements.

$$d_{waist} = \frac{2 \cdot \lambda_{laser} \cdot f}{D_b}$$

d_{waist} = beam waist diameter (equal to the diameter of the measuring volume)

λ_{laser} = laser wavelength

f = focal distance

D_b = diameter of laser beam on focal lens

The Beam Expander was capable of decreasing the diameter of the measuring volume by a factor of 1.9. This reduced size of the measuring volume was primarily the result of an increase in the diameter of the laser beam prior to its exiting the transducer and partly due to the increase in the beam separation between the coincident beams where they exited the focal lens. The effect of this decrease in size of the measuring volume was an increase in its light intensity as well as a better spatial resolution within the measuring volume.

The Beam Expander also effectively increased the collection aperture of the Backscatter Section. This was accomplished by accepting the scattered light signals through the larger lens and reducing the volume of the signals to a point where the signals were accepted by the backscatter aperture. Both of these effects affected the intensity of the backscatter signals by increasing it by a factor of 13 (Ref. 3). This signal increase significantly enhanced the measuring potential of the laser doppler velocimeter.

B. SEEDING APPARATUS

The Thermo-Systems Model 3075 Constant Output Atomizer was the device used to produce the seeding particles from olive oil (Fig. 4). The atomizer was capable of generating seeding particles which varied in size from 0.02 to 0.3 μm through the technique of solvent evaporation. Solvent evaporation involved the injecting of the seeding fluid into a stream of dry compressed air and expanding the aerosol in the atomizer assembly cavity. For this experiment, the Model 3075 was used in the non-recirculating mode; once the aerosol entered the atomizer assembly cavity, the particles that were too large to be carried by the air flow out through the upper exit were deflected by the impact plate.

A key component of the seeding apparatus was a Harvard Apparatus syringe pump. The syringe pump provided the means by which the seeding fluid was injected into the atomizer. It also provided the flexibility of having 30 different flow rates which could be selected instantaneously. Figure 4 shows the syringe pump in the foreground, and the air pressure regulators and dehumidifier are positioned to the left.

C. LASER SUPPORT APPARATUS

The two main components of the laser device, the laser beam generator and the transducer, were mounted on an aluminum optical bench which provided rigidity to the system. This rigidity maintained the alignment between the laser and the transducer and provided support for the position adjustments

associated with the transducer. Attached to the optical bench was a translational micrometer which provided the calibrated movement of the laser system during the positioning of the laser beams' focal point for data measurement. The micrometer along with an aluminum stiffening bar provided additional support to the optical bench to keep it from bending under the weight of the laser components.

The translational micrometer provided an attachment point between the optical bench and laser components and the laser support table. The wooden support table was specifically designed to support the laser system in the close confines of the transonic compressor test cell as seen in Figures 5 and 6. The table provided the abilities to incline the laser system from 0° to 25° and to raise the upper portion of the table a total of eight inches. Figure 6 shows the complete laser system consisting of the laser generator to the right, the transducer to the left, and the laser support table underneath.

D. DATA ACQUISITION SYSTEM DESCRIPTION

The data acquisition system consisted of an assortment of computers and peripheral devices that were joined together as shown in Figures 7, 8, and 9. The 55L90 Counter Processor provided the high voltage source for the photomultiplier. The photomultiplier transferred the scattered light signals to the Counter Processor. An oscilloscope received the scattered light signals and system noise from the Counter Processor on one of its channels; the other channel sampled the output of the

Interstate P24 Pulse Generator prior to its being received by the Counter Processor. This oscilloscope was also connected to the pulse generator via a line from the "SYNC OUTPUT" of the pulse generator to the "TRIG IN-EXT HOR" input. The pulse generator was connected to the PACER circuitry to take advantage of its bin position signal output. The PACER, in turn, was controlled by the HP-21MX computer with the HP-2644A Terminal handling its program input and output functions. Another oscilloscope was used to synchronize and monitor the PACER output and the one-per-blade signal being tranferred to the PACER by the HP-21MX computer. The HP-21MX system was interfaced with the HP-9825A computer by an HPIB (an interface bus). To complete the circuit, the HP-9825A computer was linked to the Counter Processor and an HP-9862 Plotter.

Figure 8 is a photograph showing the counter processor (lower left), the HP-9825 computer (lower right), an oscilloscope (upper right), and the HP-9862 plotter. Figure 9 shows the area in the Turbomachine Laboratory control room which houses the PACER system. The PACER circuitry and HP-21MX computer are located in the vertical console at the rear with the HP-2644 terminal in front of it.

IV. METHOD OF APPROACH

A. BEAM MODE SELECTION

According to Ref. 6, the 55L88 Beam Transducer, without the installation of the beam expander, had the capability for beam separations of 20, 40, and 80mm and for focal lengths of 120, 300, and 600mm. To determine what the best mode of operation was to be used in the laser velocimeter survey, an analysis involving the geometric characteristics of the compressor section and the measuring volume properties was conducted. The analysis was conducted assuming the existence of the worst operating condition which existed when the measuring volume was coincident with the compressor hub.

For each measuring volume length available, the angle from the center of the measuring volume to the outside boundary of the casing window was determined. For any mode to be useful, the half angle between the incident beams would need to be less than the angle measured above; this would insure that both beams would be able to enter the outside face of the casing window. Two of the modes failed to provide half angles small enough to meet these physical requirements. These modes consisted of focal lengths of 120mm and 300mm and beam separations of 40mm and 80mm respectively.

The analysis was continued by determining the beam separation of each mode at the casing window entrance. A comparison of the beam separations revealed that the relative differences between

them at the casing window entrance were very small. The decision of which mode to choose was based primarily upon the number of fringes available in the measuring volume for each combination of focal length and beam separation. As the result of this decision, the operating modes to be used in the velocity survey were comprised of focal lengths of 300mm and 600mm, respective beam separations of 40mm and 80mm, and respective numbers of fringes of 64 and 127. The anticipated application of these modes was the basis upon which the laser support apparatus was designed.

With the addition of the beam expander to the LDV transducer, the length of the laser system was extended by 5 inches which eliminated the use of any mode employing a 600mm focal length because the combination of the focal length and the length of the laser system exceeded the space available in the compressor test cell. The beam expander increased the transducer beam separations of 20mm and 40mm to separations of 38mm and 76mm respectively. The beam separation angle consequently increased as a result of the increased beam separation thereby eliminating the 300/76 mode due to its half-angle being too large to permit the beam pair from entering the casing window. This further elimination indicated that the beam mode which was comprised of a focal length of 300mm and a beam separation of 38mm was the only mode available to be used in the experiment. It provided thirty fringes in the measuring volume.

B. LASER SYSTEM ALIGNMENT PROCEDURE

The geometrical combination of laser inclination angle (α), table height (H), and the distance of the transducer's focal lens from the compressor outer casing wall (D), provided the means by which the laser focal point was positioned at the desired location within the compressor (Figs. 5 & 6). It was necessary to incline the laser system at the same acute angle which was formed between a horizontal axis and the radial line from the center of the compressor hub through the center of the port opening in the casing wall. The proper combination of table height and the distance from the focal lens to the compressor outer casing not only aligned the longitudinal axis of the laser transducer with the radial line that passed from the compressor hub's center through the center of the casing port opening but also placed the focal point on the hub.

To ascertain whether the focal point was in fact positioned on the hub, laser safety goggles were used to observe the reflection of the laser beams on the hub's surface. If two spots were seen, more adjustments were required until only one spot could be observed. Typical values used for the laser inclination angle, table height, and focal lens distance from the casing wall were 19°, 2 inches, and 8.2 inches respectively.

Care was taken to ensure that the longitudinal axis of the laser system was perpendicular to the longitudinal axis of the compressor section. This was done by aligning the two incident laser beams such that they were located on the relative horizontal

axis of the port opening and that the beams were aligned such that they were on opposite sides of the relative vertical axis and at the same distance from it.

With the laser focal point positioned on the hub, the beam spot was used to align the pinhole in the photomultiplier so that the reflected focal point was in focus and positioned. Once this had been accomplished, the laser system could be moved by using the calibrated translational micrometer to position the focal point at the desired radial point in the compressor for data measurements. In this experiment, the focal point was positioned at a radial distance of 1.41 inches from the compressor hub. The micrometer had the capability of traversing only one inch without surpassing the calibrated scale. To traverse 1.41 inches accurately, the micrometer was traversed 0.5 inch using its calibrated scale and then a 0.91 inch metal plug was inserted into the micrometer to attain the total required distance. With the completion of the physical alignment of the laser system, the focal volume was positioned at its desired location behind the rotor trailing edge at an axial distance of 0.41 inch. At this position, a blade pair was 3.49 inches in width.

To test the alignment prior to running the compressor, the tube carrying the seeding particles from the atomizer was placed at the port opening such that it directed the particles at low velocities into the compressor while the laser was turned on. The particles would not traverse the interference pattern as they entered the compressor but circulated turbulently after

striking the compressor hub. This turbulent motion allowed some of the particles to traverse the measuring volume across the fringe pattern thereby producing scattered light signals.

By adjusting the bandpasses and amplitude on the counter processor, the classic doppler burst was observed on an oscilloscope (Fig. 10). The doppler burst patterns were only attained if a well-defined fringe pattern was produced and the image of the focal point had been positioned and focused properly on the pinhole at the photomultiplier aperture. Another indication included a high validation rate from the counter processor on the order of 850 particles/1000 or better.

C. DATA ACQUISITION SYSTEM OPERATION

The data acquisition system was developed, for the most part, specifically for the purposes of this study. The system provided the method by which flow velocities in the compressor could be measured and processed to study the velocity flow field at the same position behind each of the blade pairs. The part of the system which was already well established in its operation was the PACER system (Ref. 7) installed in the control room of the Naval Postgraduate School Turbomachine Laboratory (Fig. 9).

Knowledge of the data flow was necessary to understand the overall problem solution (Fig. 7). The scattered light, reflected off a particle transiting the fringe pattern, was detected by the photomultiplier. This photomultiplier output was observed on an oscilloscope for the purpose of viewing the signal characteristics and intensity level as well as the

magnitude of the system noise level after the signal had passed through the amplifier section of the counter processor. The oscilloscope was used in conjunction with the amplifier gain and threshold setting switches to optimize the signal-to-noise ratio. The amplifier gain was used to lower the average noise level below 50 millivolts and simultaneously placed the signals above 50-millivolt levels. The threshold setting switches were used to vary the threshold level until a high validation rate was achieved.

The oscilloscope was also used to observe on its other channel the data acquisition window which was generated by the PACER equipment and the pulse generator. The oscilloscope displayed the window width, the stability of the pattern, and the time between windows. A typical window width for this study was 2.0 μsecs to 4.0 μsecs.

The pulse generator generated the data acquisition window. The pulse generator was interconnected with the PACER such that the one-per-blade signal was used to trigger the pulse generator which, in turn, sent the pulse of the desired width to the counter processor. Whenever the pulse was not present in the counter processor, it was inhibited from transferring the raw doppler frequency data to the HP-9825. This process permitted the measurement of data at prescribed bin locations behind each of the blade pairs.

The HP-9825 accepted the data from the counter processor when data was available for transfer and stored it in a data buffer until a desired number of doppler frequencies had been

accumulated. Each of the raw doppler frequencies was processed by the HP-9825, and the average of all of the frequencies was computed and converted to a flow velocity component. The combination of flow velocity magnitude in feet per second and bin position was transferred to the HP-9862 Plotter to maintain a graphical representation of the acquired data.

The HP-9825 was interfaced with the HP-21MX computer which acted as the controller for the PACER system. The HP-9825 transferred its resulting doppler frequency as each was computed to the HP-2644A Terminal for output on its display and its peripheral teletype. Once it had received this information, the control program and the HP-21MX computed the next bin position to be used in the acquisition of the data and re-initiated the process.

Table IV is a listing of the controlling program for the data acquisition system. The program was used in conjunction with the "BASIC" program designed for the HP-21MX computer. Its purpose was to initiate the PACER sequence where the PACER triggered the pulse generator which uninhibited the counter processor. After the HP-9825 (logical unit #10) had interfaced with the HP-21MX declaring that it had finished acquiring and processing data for a particular bin location, the program updated the PACER to take data at the next bin position. The program would continue in a loop until the last bin position requested in line 20 had been investigated. After the HP-9825 had completed processing its data, it transferred its resulting average doppler frequency to the HP-21MX; the HP-21MX displayed

this frequency along with its corresponding flow velocity component, the bin position, and the compressor rpm indicator on the console display of the HP-2644A Terminal and the teletype (logical unit #14).

V. RESULTS AND DISCUSSION

A. DATA RESULTS

The experiments for obtaining the data for the axial and tangential components of the flow behind the rotating rotor stage of the transonic compressor were conducted under the conditions of Table I. This table lists the settings for the counter processor and the HP-9825 as well as the compressor performance data. The experimental operating conditions were essentially steady-state conditions due to their being reproducible for each experiment.

The axial flow velocity component was observed to have a higher velocity magnitude and a weaker wake structure as compared to the results of the tangential velocity component measurements. Figure 11 shows the axial velocity measurements as they varied with bin number. The non-wake structure exhibits a mean velocity magnitude of 328 ft/sec with a standard deviation of ± 18.9 ft/sec. The two wake structures are characterized by the decrease in velocity magnitude. The first wake reached a minimum velocity of 254.49 ft/sec at bin position 77 while the second wake attained a minimum velocity of 254.67 ft/sec at bin position 201. From this data, it was determined that the first wake was 14 bins in width and the second wake was 10 bins in width. Using the end of the first wake and the beginning of the second wake as reference points, it can be seen that the wakes were separated by 116 bin widths.

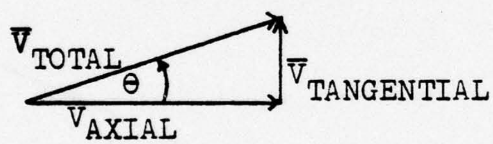
The tangential flow velocity component measurements as seen in Fig. 12 show not only an increase in velocity in the wake but also a more well-defined wake structure. The mean velocity magnitude of the non-wake regions was 175 ft/sec with a standard deviation of $\pm$ 6.9 ft/sec. A sharp increase in velocity magnitude identifies the two wake structures. The first wake reached a maximum velocity of 335.48 ft/sec at bin position 71 while the second wake achieved a maximum velocity of 338.16 ft/sec at bin position 201. The widths of the first and second wakes were observed to be 14 and 12 bin widths, respectively. Using similar references as with the axial velocity measurements, it was found that these wakes were separated by 120 bin widths.

Figure 13 represents the total flow velocity magnitudes over a range of bin positions. The value for the magnitude of each total velocity was calculated from the axial and tangential velocity measurements that corresponded to a common bin position. The total velocity was determined using the following equation:

$$V_{TOTAL} = \sqrt{V^2_{AXIAL} + V^2_{TANGENTIAL}}$$

For the non-wake regions of Fig. 13, the mean total velocity was 372 ft/sec. The wake structure is not as well defined in this graph as it appeared in Figs. 11 and 12 and lacks any significant change in velocity. Since the total velocity vector is defined not only by the total velocity magnitude but also the flow's yaw angle, this indicates that the passage of the rotor blade affects to a higher degree the direction of the flow rather than changing the total velocity of the flow.

This effect is observed in Fig. 14 where the yaw angle of the total flow as referenced to the axial direction is plotted over a range of bin positions. This graph depicts well-defined wakes with maximum yaw angles for the first and second wakes of 50.20° at bin position 69 and 53.02° at bin position 201, respectively. The non-wake regions exhibit a mean yaw angle of 28.06° with a yaw standard deviation of ±1.80°. Therefore, the passage of a blade causes a maximum change in yaw angle of 22.14° for the first wake and 24.96° for the second wake. As with the magnitude of the total velocity, the yaw angle was derived from the axial and tangential velocity measurements that corresponded to a common bin position. The yaw angle was calculated using the following vector diagram and equation:



$$\Theta = \mathrm{TAN}^{-1} \frac{V_{TANGENTIAL}}{V_{AXIAL}}$$

Turbulence intensities were determined by the HP-9825 computer program (see Appendix A and Table II) for the axial velocity component measurements and the tangential velocity component measurements. Even though only four data values were used to determine the velocity measurement at each bin position, an increase in the turbulence intensities of the wake regions as compared to those of the non-wake region was evidenced for the tangential velocity component measurements.

B. DATA COMPARISON

Reference 8 contains data obtained by pressure probe measurements representing the wake structure behind the rotating rotor section of the transonic compressor. The results of these experiments can only be qualitatively compared to those of Ref. 8 due to the data being obtained under different compressor operating conditions. In comparing the yaw angles measured in these experiments with those of Ref. 8, the present measurements indicate narrower wakes, a greater change in yaw angle, no evidence of an aperiodic wave structure in the non-wake regions, and a larger average yaw angle for the non-wake regions.

VI. CONCLUSIONS

The laser doppler velocimetry system was shown to be capable of measuring the axial and tangential velocity components of the flow behind the rotating rotor blades of the transonic compressor. The data was characterized by the presence of two well-defined wake structures which represented the passage of a pair of rotor blades. The wake structures of the axial and tangential velocity component data were located at the same bin positions and were of comparable widths. From these measurements, the flow was further analyzed to determine the total velocity vector, its magnitude and direction, over the range of bin positions. Turbulence intensities were also determined to study the turbulent nature of the flow in the wake and non-wake regions for both the axial and tangential directions. A qualitative comparison of this data with data obtained from pressure probe measurements was performed.

To further verify the data from these investigations, additional laser doppler velocimetry data should be acquired, particularly data that can be quantitatively compared to data obtained previously by other methods. It is also recommended that similar experiments be performed by taking data behind a particular pair of blades as was accomplished in Ref. 8.

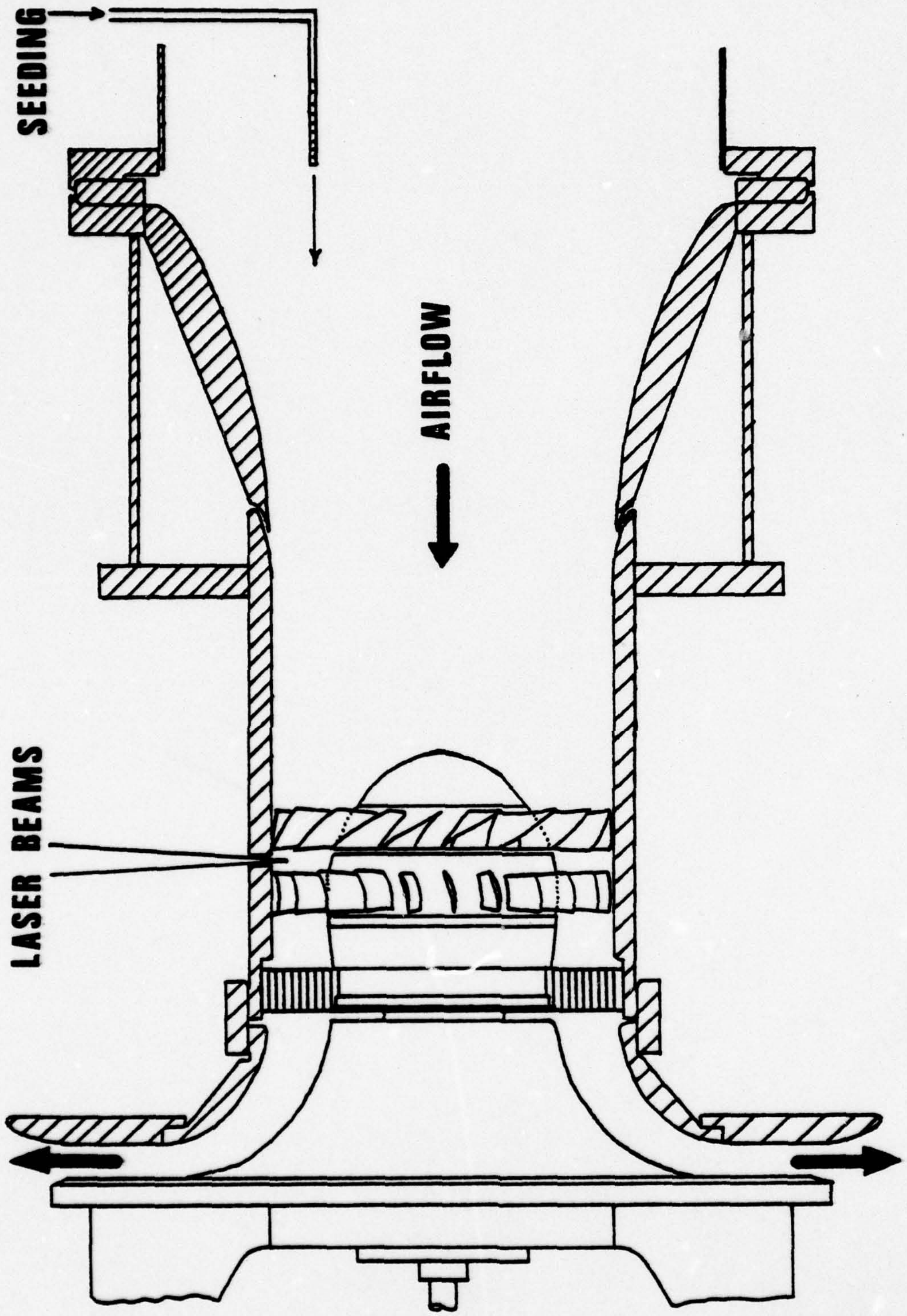
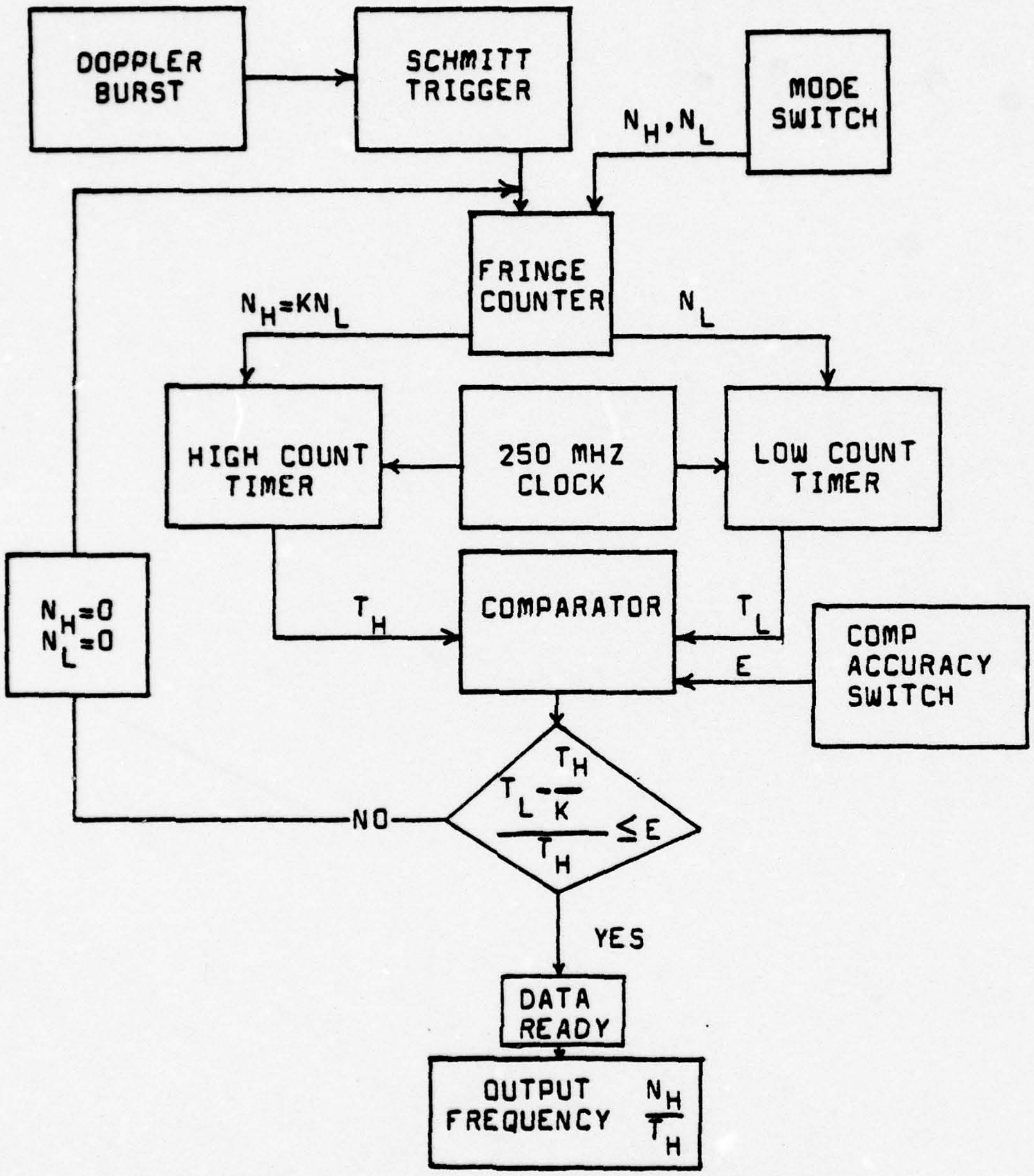


FIGURE 1. TRANSONIC COMPRESSOR



LDV COUNTER PRINCIPLE

FIGURE 2

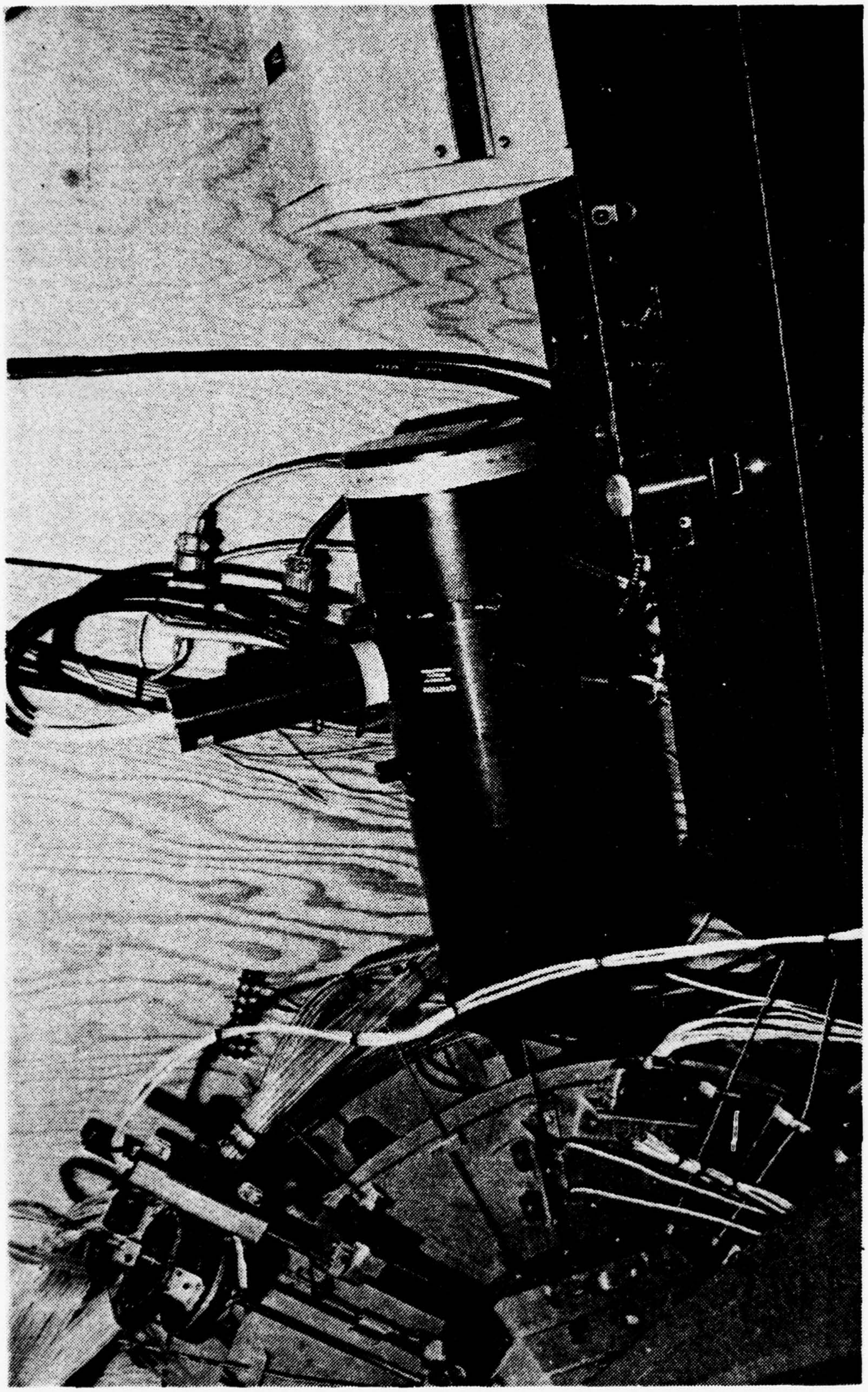


FIGURE 3. LASER TRANSDUCER IN ALIGNMENT AND OPERATING POSITION

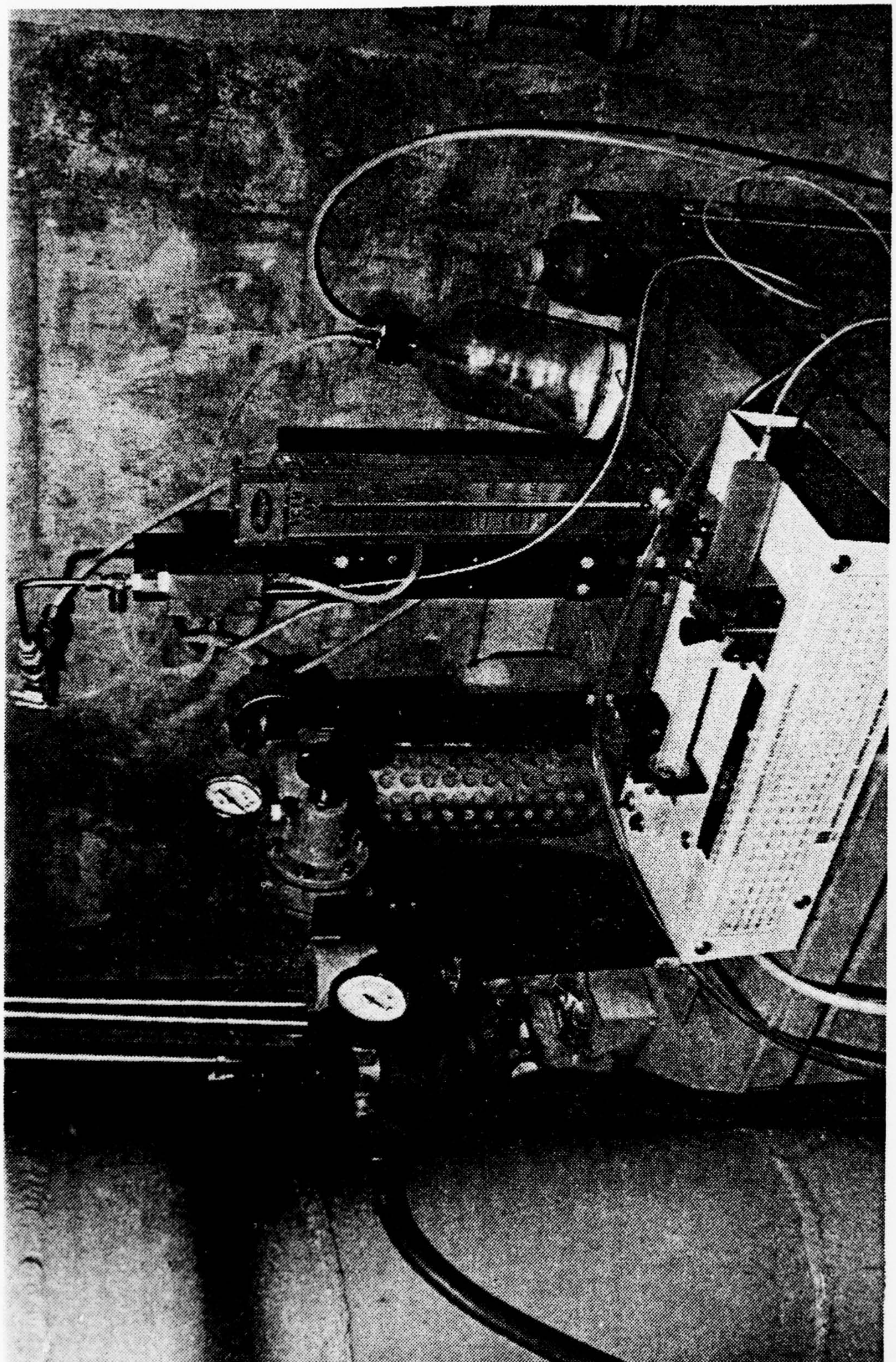


FIGURE 4. ATOMIZER AIR SUPPLY SYSTEM

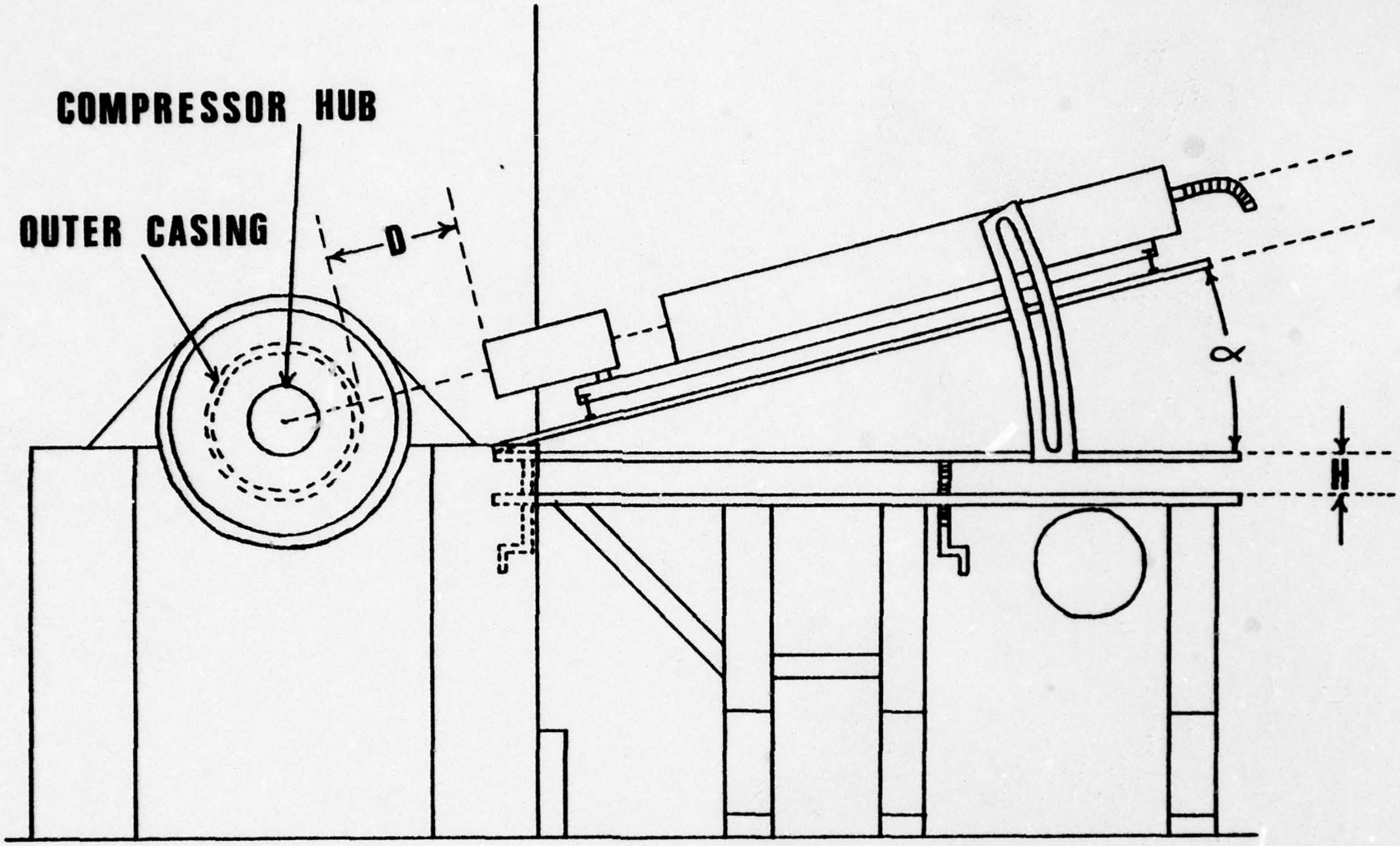


FIGURE 5. LASER ALIGNMENT GEOMETRY

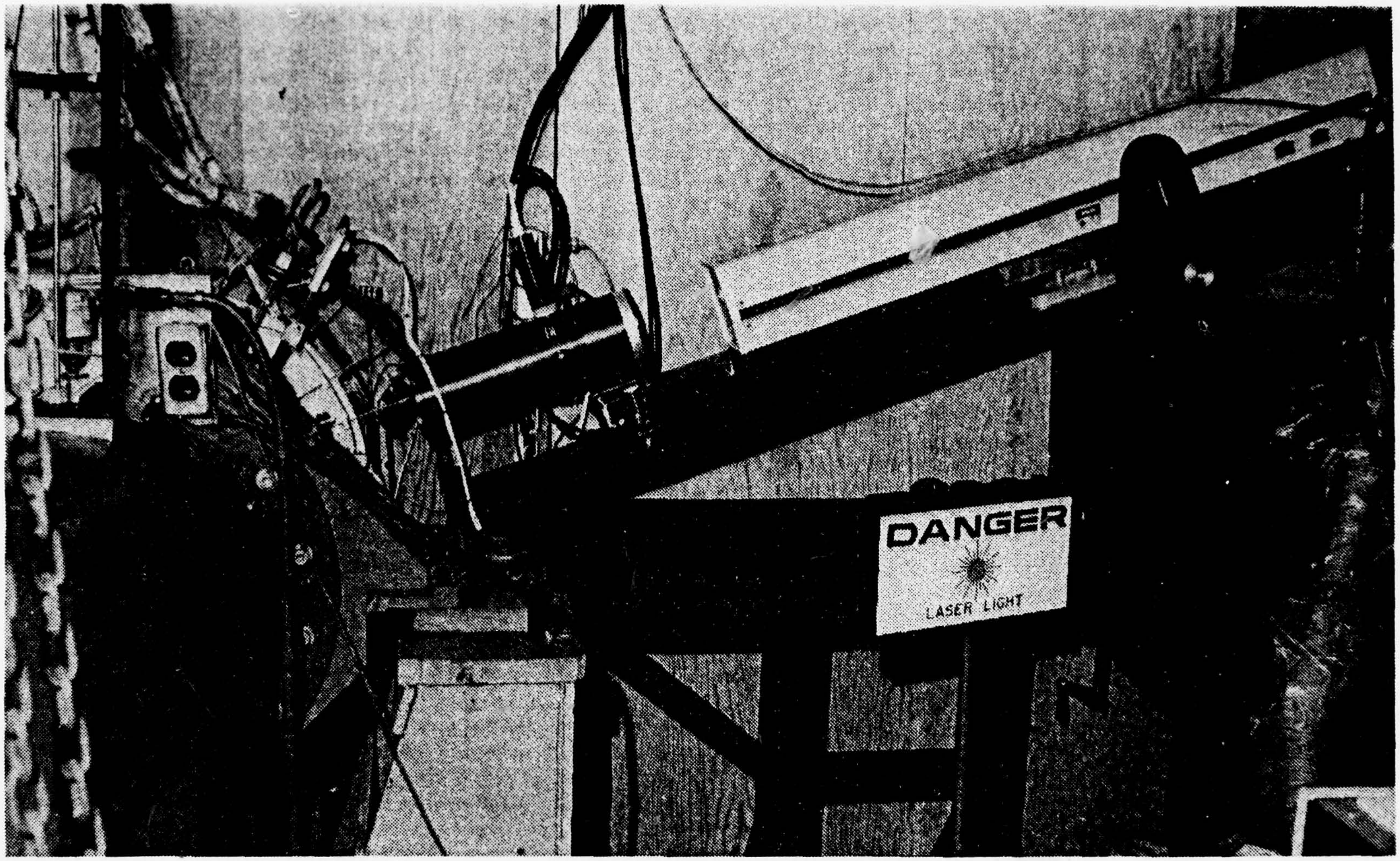
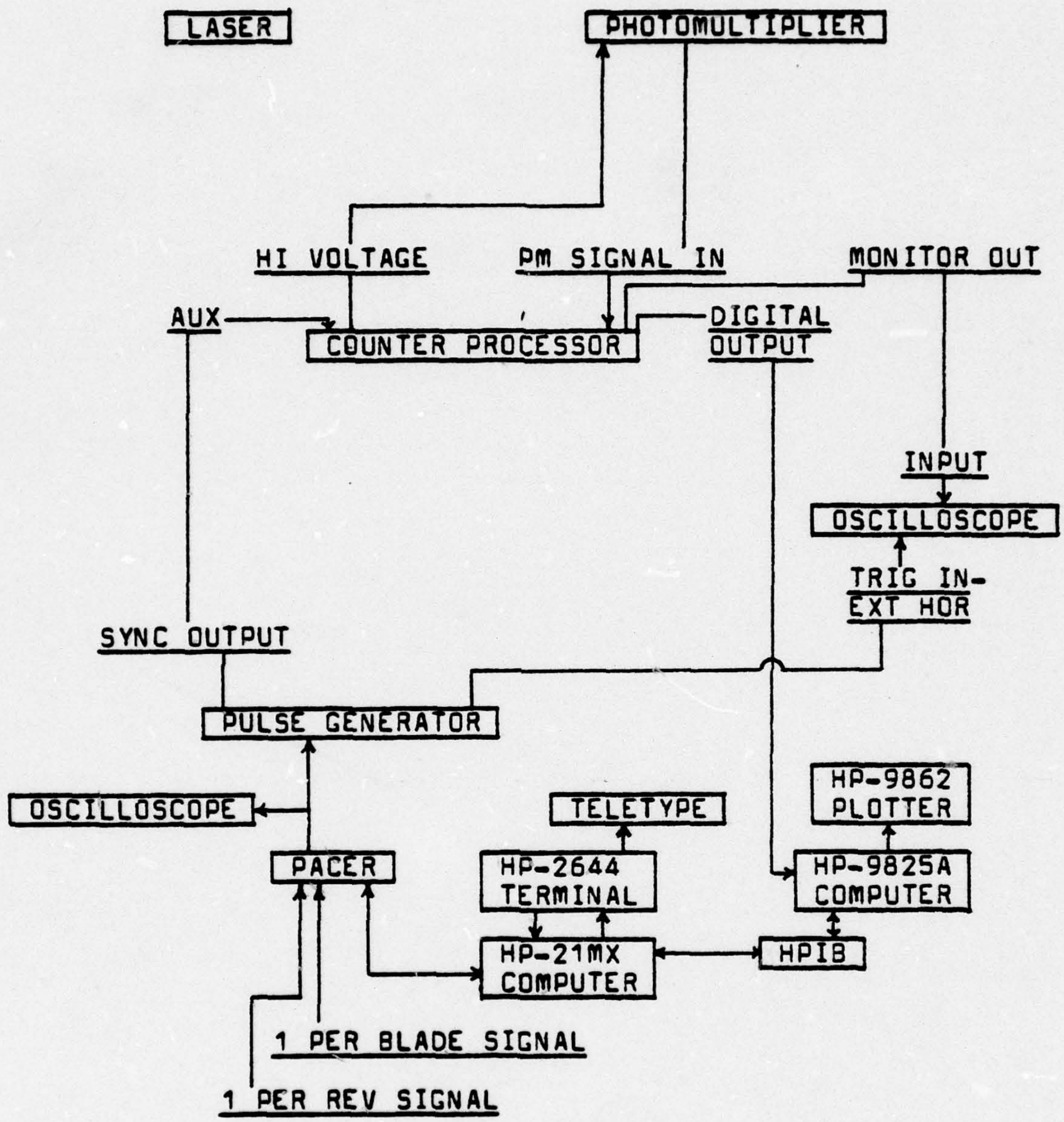


FIGURE 6. LASER SYSTEM IN ALIGNMENT AND OPERATING POSITION



DATA ACQUISITION SYSTEM

FIGURE 7

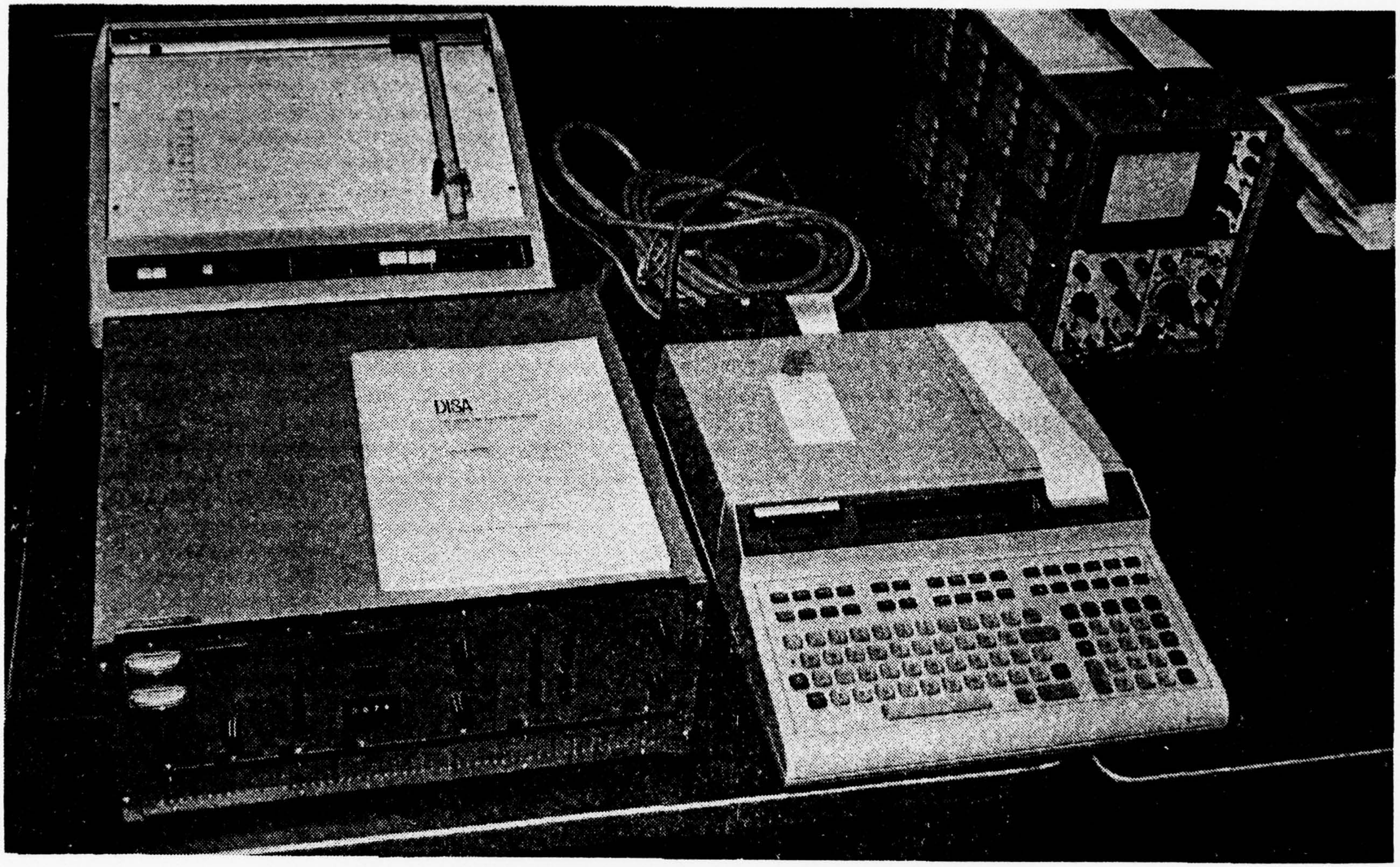


FIGURE 8. COUNTER PROCESSOR, HP-9825 COMPUTER, OSCILLOSCOPE, AND PLOTTER

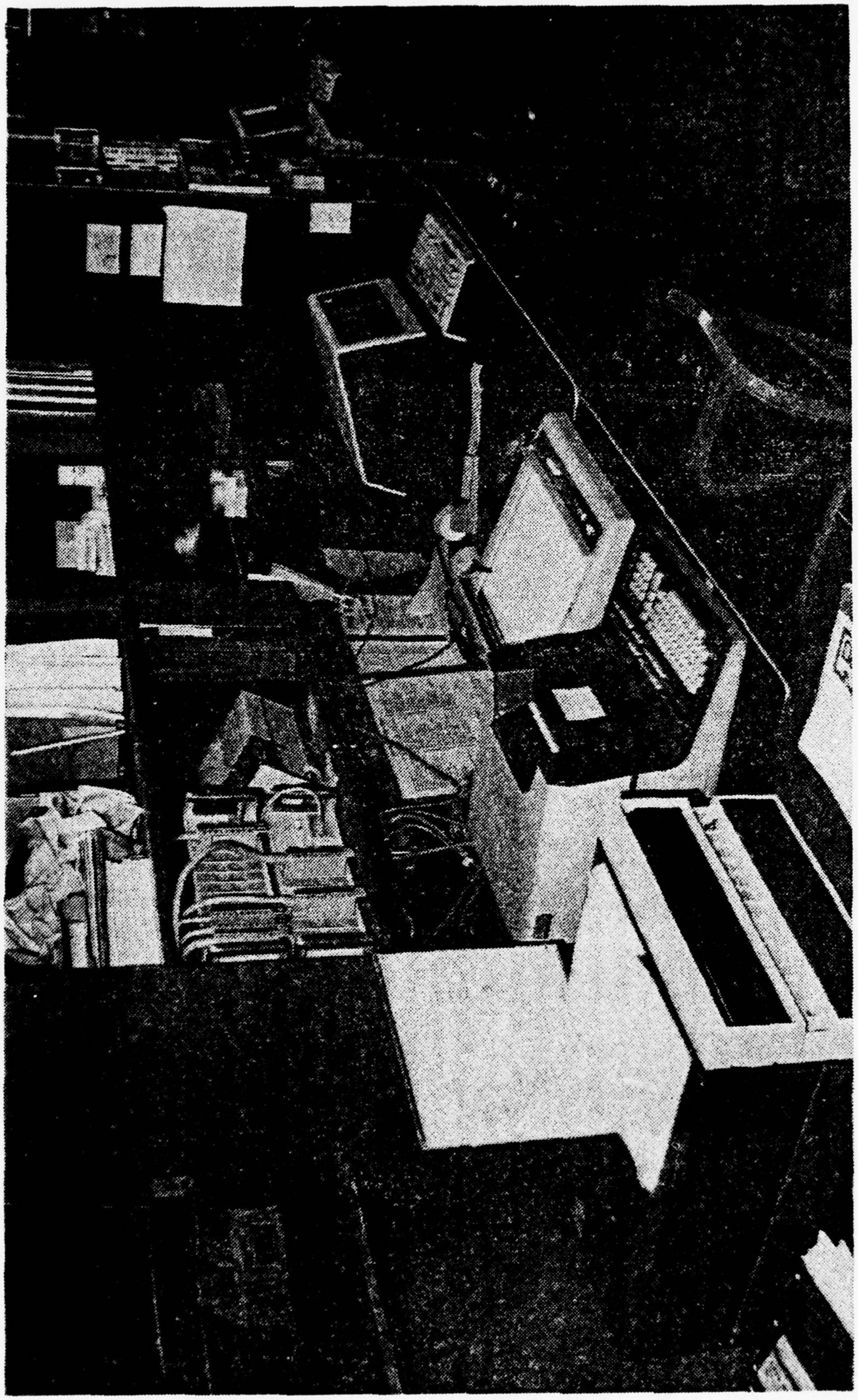
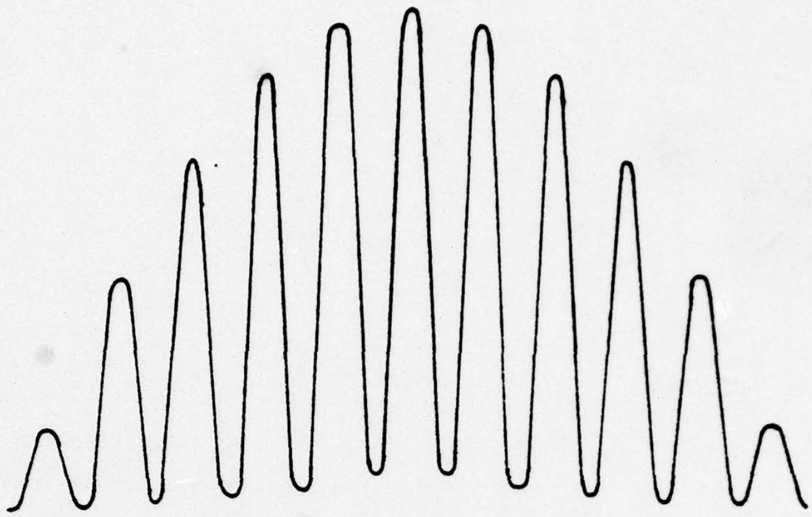
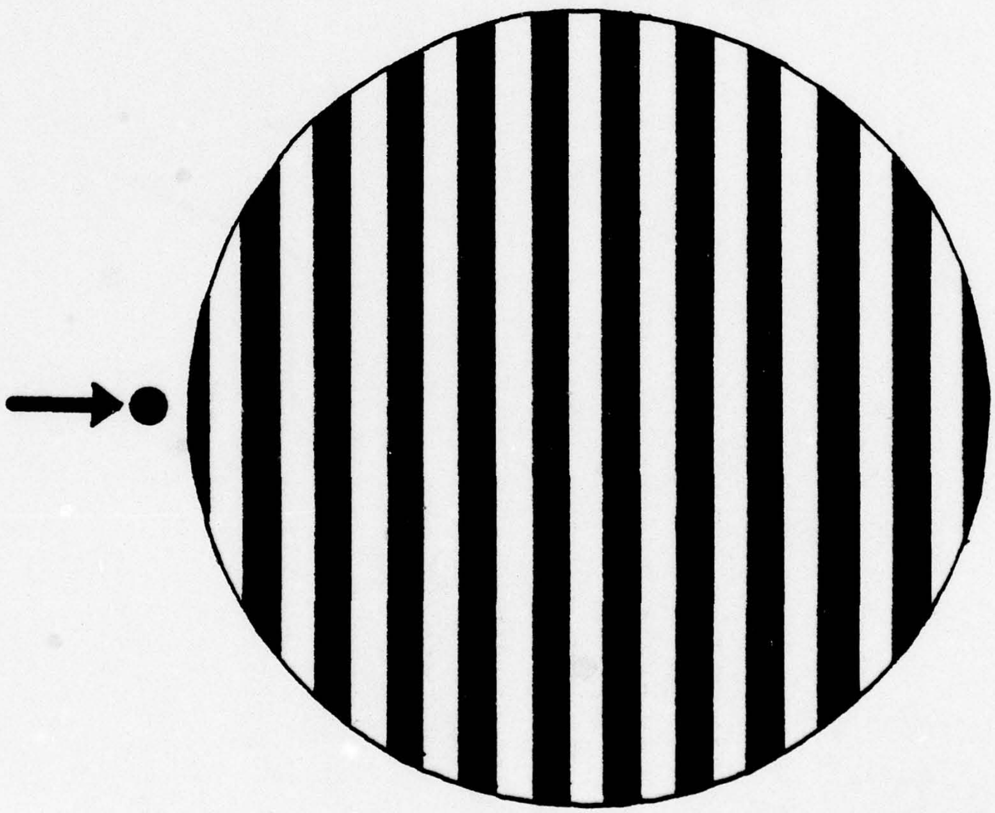


FIGURE 9. PACER SYSTEM

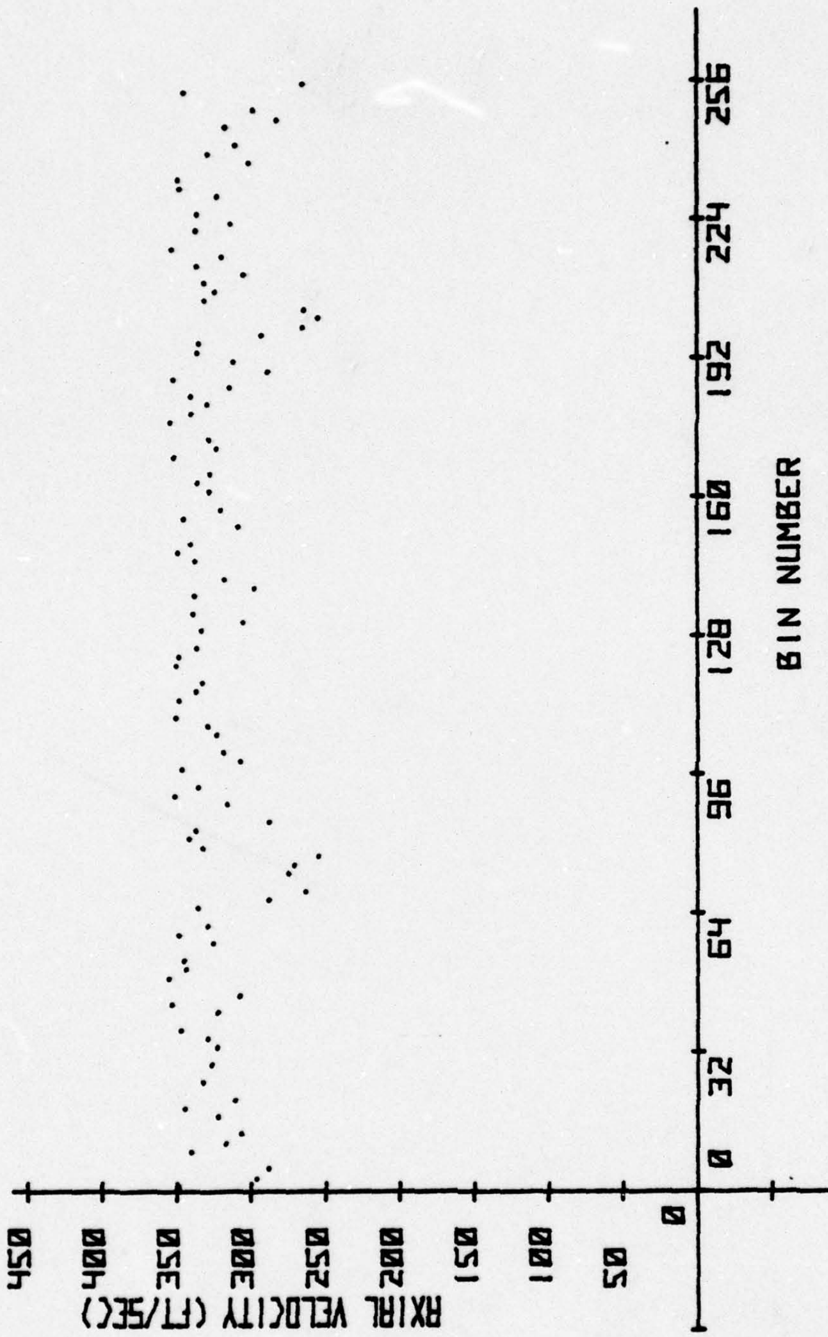


CLASSIC DOPPLER BURST



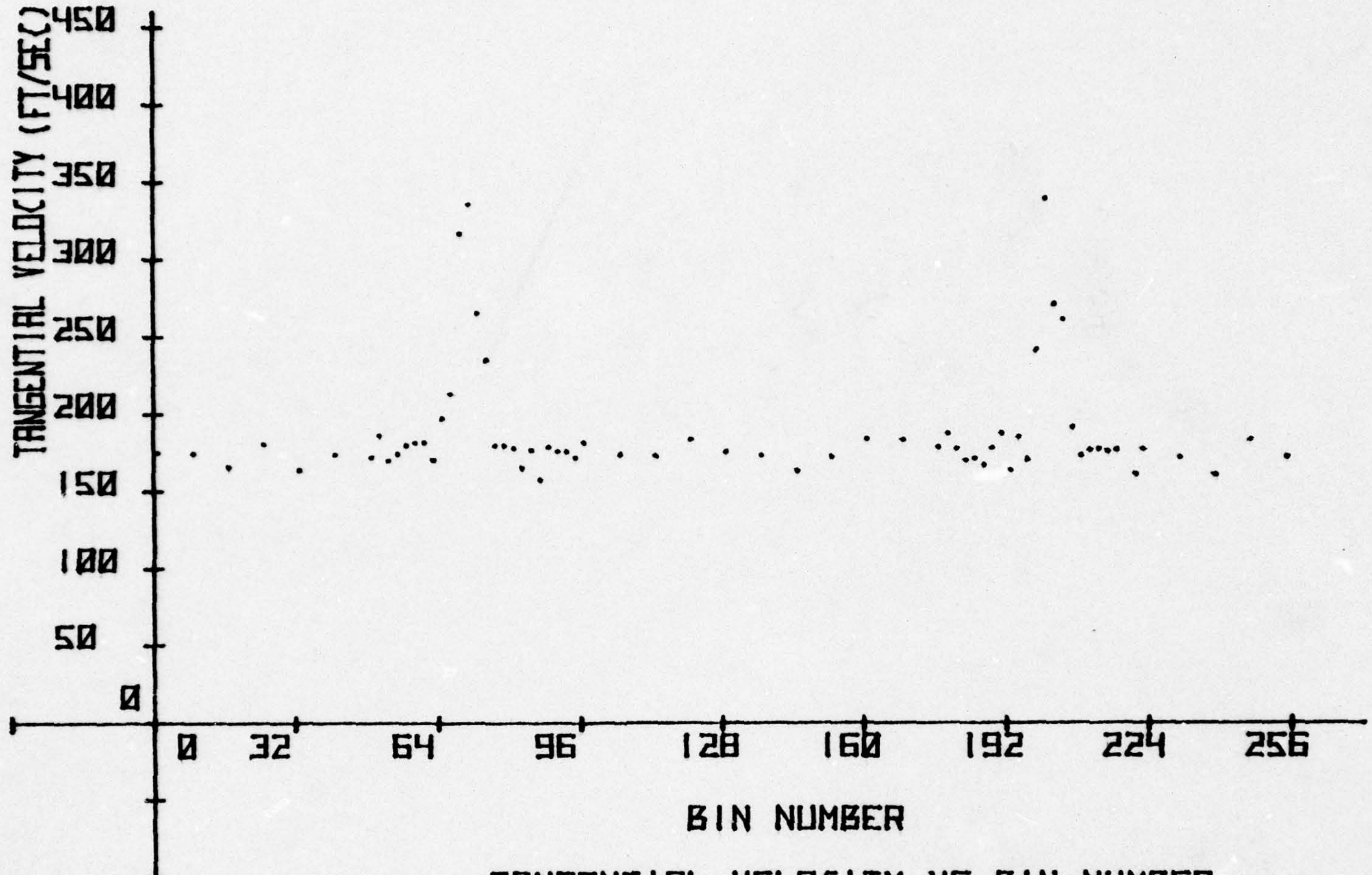
INTERFERENCE PATTERN

FIGURE 10



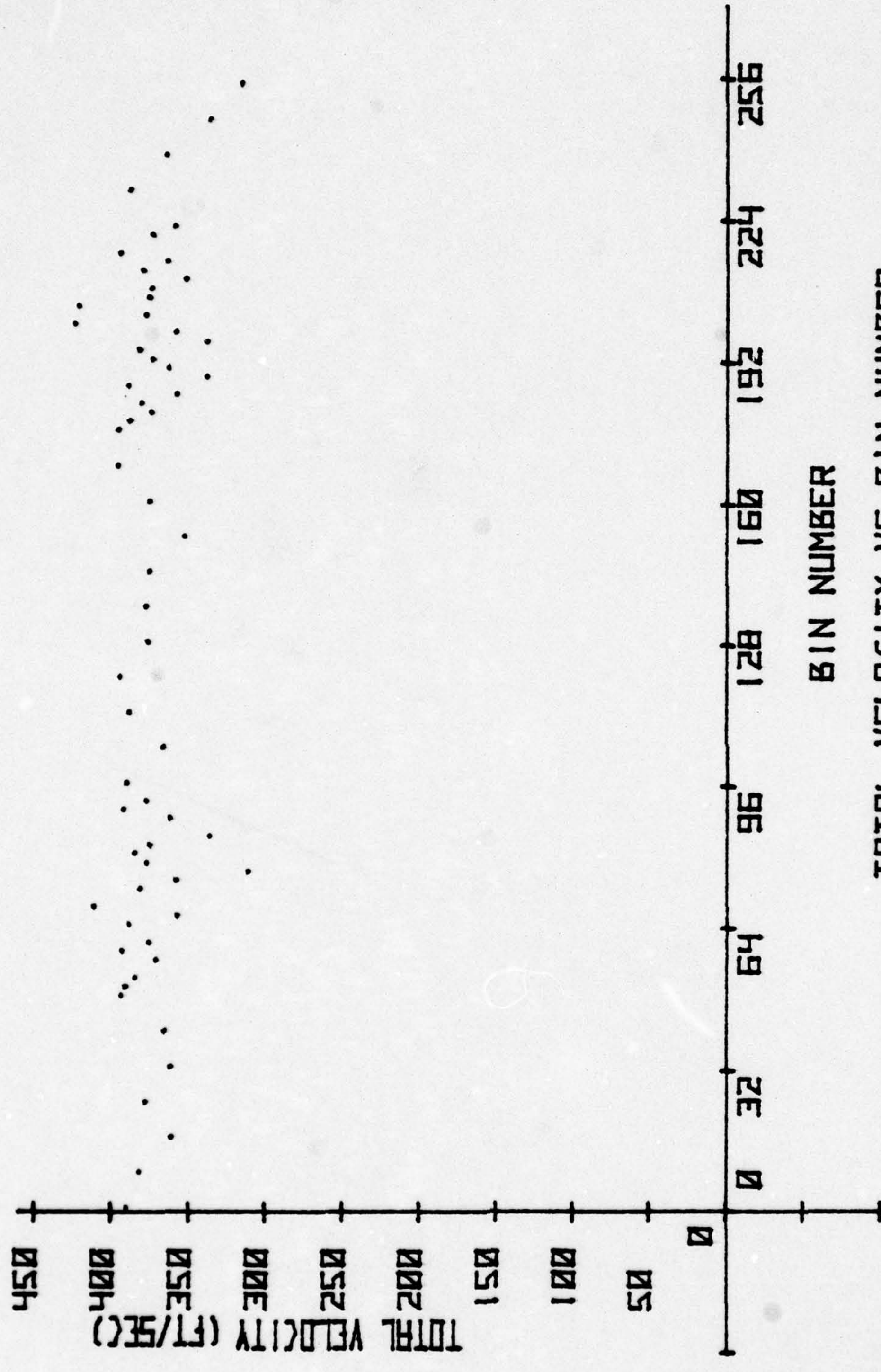
AXIAL VELOCITY VS BIN NUMBER

FIGURE 11



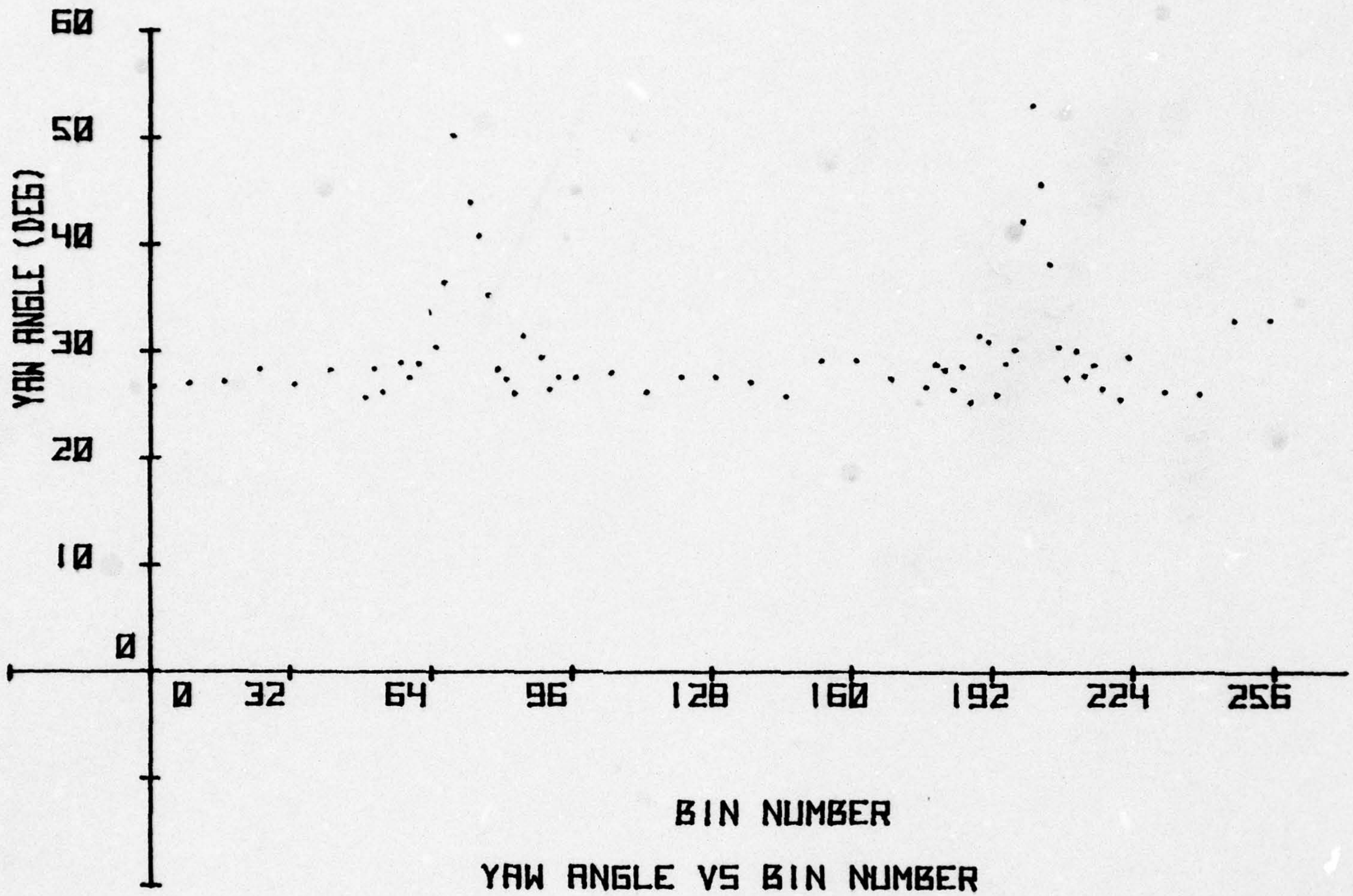
TANGENTIAL VELOCITY VS BIN NUMBER

FIGURE 12



TOTAL VELOCITY VS BIN NUMBER

FIGURE 13



YAW ANGLE VS BIN NUMBER
FIGURE 14

TABLE I

EXPERIMENTAL OPERATING CONDITIONS

Counter Processor		
Threshold window:	16db	
Amplifier gain:	-7db	
Photomultiplier voltage:	1.3-1.4kv	
Anode current:	10 μA	
Comparator accuracy:	12%	
	Axial	Tangential
Validation rates:	938	888
Low pass filter:	$100X10^6$	$100X10^6$
High pass filter:	$16X10^6$	$8X10^6$
HP-9825 Computer		
	Axial	Tangential
Low pass filter:	$100X10^6$	$100X10^6$
High pass filter:	$17X10^6$	$8X10^6$
Laser power setting:	0.3 watts	
Seeding probe position:	320^o/6.5 inches	
Syringe pump position:	14	
Air flow rate:	55 ft^3/HR	
Oscilloscope		
Delay:	1 μsec	
Vertical scale:	0.05 Volts	
Data acquisition window:	4 μsec	

TABLE I (continued)

Compressor Performance Data

RPM = 15330	
Pressure ratio (total-total):	1.1242
Referred flow rate:	10.2609 lb/sec
Total temperature in:	68.12°F
Estimated average total velocity and yaw angle:	400 ^{ft}/sec and 27.54°

Pulse Generator

Trigger mode selected	
Repetition mode:	1HZ
Delay:	10 nanoseconds
Pulse width:	1 μsec (adjusted to 2 μsec)
Rise/fall time:	5 nanoseconds
Amplitude:	5 volts
Output polarity:	+

TABLE II

HP-9825 DATA ACQUISITION AND PLOTTING PROGRAM

```
0:  1 → N
1:  ent "low pass filter", H;Ø → I; prt "low pass=",H
2:  ent "high pass filter",L; prt "high pass=",L
3:  ent "how many blocks of points",r6;Ø → V
4:  buf "DAT 1",4,4;Ø → r4;Ø → r5;Ø → M; buf "DAT 2",4,4;
       gsb "DATA"
5:  I+1 → I;moct;if r1=1;rdb("DAT 1") → D
6:  if r1=1;rdb("DAT 2") → D
7:  cmpD → D;shf(D,4) → D;band(D,17) → r2
8:  shf(D,4) → D;otdD2 ↑ otdr2 → D;mdec
9:  D1Ø↑9/13369344Ø → D
10: if D>H; Ø → D
11: if D<L; Ø → D
12: if D=Ø; gto 14
13: 1/D+r4 → r4;r5+1 → r5;D+V → V
14: if I=4; gto 16
15: jmp -1Ø
16: r5/r4 → M;V/r4 → R;Ø → I; √(R-MM)/M → R; wrt 731,M
17: gsb "PLOT"
18: prt M,4.77M,R,r5;Ø → r4;Ø → M;Ø → V;Ø → r5; gsb "DATA"
19: jmp -14
20: "DATA":
21: if rds("DAT 1")=Ø;tfr 2, "DAT 1",4
```

TABLE II (continued)

```
22:  dsp "BUFFER 1"
23:  if rds("DAT 1")=-1; jmp -1
24:  gto 3Ø
25:  if rds("DAT 2")=Ø;tfr 2, "DAT 2",4; gto 31
26:  dsp "BUFFER 2"
27:  spc
28:  gto 29
29:  ret
30:  if rds("DAT 1")=4;2→r1; gto 25
31:  if rds("DAT 2")=-1; jmp Ø
32:  if rds("DAT 2")=4;1→r1; ret
33:  gto 3Ø
34:  "PLOT":
35:  scl -32,272,-1ØØ,65Ø; csiz 2,2.5,1,Ø
36:  plt N,M*1.34Ø427e-5
37:  N+1→N
38:  pen
39:  ret
```

TABLE III

VELOCITY VERSUS BIN NUMBER
GRAPH ROUTINE

```
0:  scl -32,272,-1ØØ,65Ø; csiz 2,2.5,1,Ø
1:  plt 1ØØ,-1ØØ,1
2:  lbl "VELOCITY VS BIN NUMBER"
3:  cplt -16,2
4:  lbl "BIN NUMBER"
5:  csiz 2,2.5,1,9Ø
6:  plt -25,25Ø,1
7:  lbl "VELOCITY (FT/SEC)"
8:  axe Ø,Ø,32,5Ø
9:  csiz 1.5,1.7,7/1Ø,Ø
10: Ø→Y
11: plt Ø,Y,1
12: cplt -7,-.Ø3
13: lbl Y
14: Y+5Ø→Y
15: if Y <= 6ØØ; gto 11
16: csiz 1.7,1.7,7/1Ø,Ø
17: Ø→X
18: plt X,Ø,1
19: if X=Ø; gto 22
20: cplt -3,-1
21: gto 23
22: cplt .2,-1
```

TABLE III (continued)

```
23:  lbl X
24:  X+32 → X
25:  if X <=256; gto 18
26:  pen
27:  end
```

TABLE IV

DATA ACQUISITION CONTROL PROGRAM

```
10    DIM M$[12], A$[3]
11    CALL HPIB (7,0,0)
20       FOR X1 = 0 TO 255 STEP2
30       CALL RPACE (12,R1,X2)
40       READ #10; M
45       PRINT #14; X1,R1,M,1.34043E-05*M
50       PRINT X1,R1,M,1.34043E-05*M
60       NEXT X1
70    END
```

NOTE: If it is desired to take data at a particular blade pair, the following statement should be inserted into the program:

```
25       LET X2 = -(32678-X1)
```

APPENDIX A

HP-9825 DATA ACQUISITION PROGRAM

The program found in Table II is a listing of the HP-9825A program which handled the data acquisition process. The HP-9825A uses a high level programming language known as HPL which is designed specifically for scientists and engineers. HPL provides adequate power and efficiency for handling equations, data manipulation, and input/output operations with many of its operations similar to corresponding BASIC commands. The following is an explanation of the commands and the flow of program execution which were incorporated by the data acquisition program.

A. MAIN PROGRAM

The main program initially assigned a value (normally 1) to the counter "N" which corresponded to the number of the first bin that was to be investigated in the wake survey. A value for the low pass filter, the upper limit of the program's bandpass, was entered and stored in "H". At this point, the counter "I" was initialized to zero; "I" was a counter which monitored how many doppler frequencies had been accepted into storage prior to being filtered by the established bandpass. The high pass filter, the lower limit of the program's bandpass, was next entered and stored in "L". The bandpass of the computer program did not necessarily have to be exactly the same limits as those that were programmed on the counter processor; however, the two

bandpasses must intersect one another or no data flow from the counter processor to the HP-9825 would have occurred. A dummy quantity of "r6" was filled with the "number of blocks of points" desired, and the quantity "V" was given a value of zero where "V" was to be the summation of doppler frequencies attained that were not filtered out by the computer bandpass.

The "buf" commands in step 4 established "DAT 1" and "DAT 2" as read/write buffers that were used for buffered DMA (direct memory access) operation and assigned its data source as the counter processor. Initialization was performed for the quantities of "r4", "r5",and "M". The subroutine "DATA" was called to accept data into the two buffers for later processing.

Once the "DATA" subroutine returned program execution to step 5 of the main program, the data processing commenced. The "I", buffer data counter, was initiated and the octal mode was established. When the computer was operating in the octal mode, all 16-bit parameters were assumed to be expressed as octal numbers. Such was the case with the data stored in buffers "DAT 1" and "DAT 2". For operational efficiency purposes,only the data in "DAT 2" was to be processed. Using a "rdb" command, one 16-bit binary character code was retrieved from "DAT 2" and stored as the quantity "D". The logical complement of "D" was determined. Due to the fact that the four least significant digits were of no significance, the data string was shifted four bits to the right to discard the worthless data. As arranged, the least four bits represented the exponent to which the number 2 was raised to finally formulate the doppler frequency in decimal.

To isolate the exponential data from the remainder of the data string, the character code was compared to octal number 17 in a logical "and" operation which in effect eliminated the upper twelve bits and saved the lower four bits which were stored in the quantity "r2". The original data string was not destroyed by this "band" command and was used for further processing. Now that the exponential term had been duplicated and stored, the data string was then shifted again four bits to the right to eliminate the exponent data from the data string.

The low eight bits of this raw data string represented the mantissa that corresponded to the exponent retrieved previously. Both the octal values of the mantissa and the exponent were converted to their decimal equivalents using the "otd" command. As specified in step 8, the decimal equivalent of the mantissa was multiplied by 2 raised to a power which was the decimal equivalent of the exponential term. Once this had been completed, the decimal mode was established for the execution of the remainder of the program. The resulting number of the mantissa-exponent recombination was further processed by a number described in chapter 6 of Ref. 5 to convert the raw data to a doppler frequency in hertz at which time it was also printed for reference on the paper tape.

Up to this point, it was possible for both the noise components and the actual doppler frequency data to have been acquired in the buffers, manipulated and processed to obtain the resulting frequencies. However, the next step was to compare the frequency

with the bandpass; if the frequency did not fall within the limits of the bandpass, it was reset to zero so as to ignore it with regards to further data reduction. Otherwise the desired doppler frequency data was allowed to proceed and to be accumulated in quantities "r4" and "V". "r4" was defined as the summation of the inverse of each doppler frequency and "V" was the summation of all doppler frequencies that were not eliminated by the bandpass up to a maximum number of 4. A loop was set up between steps 5 and 15 which continued the above acquisition, manipulation, and processing of data until "DAT 2" had relinguished all four of its 16-bit binary character codes.

Once all four data strings had been retrieved and processed, the program continued by determining the average doppler frequency "M" and the square of the variance "R", otherwise called the square of the turbulent intensity. The average doppler frequency was transferred from the HP-9825 to the HP-2644A Terminal for visual display on its console and for printing on its peripheral teletype. The "PLOT" subroutine was then called to graphically plot the flow velocity and bin number on the HP-9862 plotter. When program execution was reassigned to the main program, the program printed the average doppler frequency, the corresponding flow velocity, the squared variance multiplied by 100, and the number of valid doppler frequencies received. All the parameters "r4", "r5", "M", and "V" were then initialized and the subroutine "DATA" was called to acquire new data. Main program execution then proceeded

back to step 5. The program continued until it was commanded to cease either by the operator or the HP-21MX controlling computer.

A2. SUBROUTINE "DATA"

The "DATA" subroutine controlled the actual acquisition for the program. The subroutine initially checked the status conditions of "DAT 1" or buffer 1. If the status of "DAT 1" was zero, meaning that the buffer was ready to accept new data, 2 bytes of data were transferred from the counter to buffer "DAT 1". "BUFFER 1" was displayed on the visual readout of the HP-9825 to indicate that Buffer 1 or "DAT 1" had just received some new data. The status conditions of buffer "DAT 1" were checked to determine if the buffer was busy which was signified by a -1. If this were the case, a loop was set up by which the program execution jumped to the line prior to this status check statement and returned to recheck the status of "DAT 1". This continued uninterrupted until the status of "DAT 1" changed to some value other than -1. Once this occurred, the status condition was checked again, but this time a status for "DAT 1" of 4 was being sought to indicate that the buffer now held four pieces of data and was ready to have the data processed using "r1" with a value 2 to indicate that it was buffer 1 that was full vice buffer 2. Once buffer 1 or "DAT 1" was full, then buffer 2 or "DAT 2" was filled using the same procedure and using the same status checks as with buffer 1 to determine the condition of buffer 2. Once it had been confirmed

that "DAT 2" contained its four pieces of data,"r1" was given a value of 1; and program execution was returned to the main program.

A3. SUBROUTINE "PLOT"

The "PLOT" subroutine was utilized to plot the points on a graph of velocity and bin number as they were being computed. It initially scaled the 8½" by 11" piece of paper to the same scale as the axis drawing program used (Table III) and selected the size of labelling characters to be used even though labelling was not to be accomplished during this sequence. The subroutine then plotted the data point with the bin number as its abscissa and the flow velocity as its ordinate. The velocity was determined by multiplying the doppler frequency by a constant which concurrently converted it to a velocity of dimensions meters/sec and then to a velocity in feet/sec. The bin number was updated to the next point to be taken either by adding 2 or 8 to its value depending on whether data was being taken in the expected wake region or out of the wake region respectively. The raising of the plotter's pen was executed next and program execution was returned to the line following the **gsb** "PLOT" statement.

APPENDIX B

DEVELOPMENT OF THE HP-9825 PROGRAM

Knowing that the doppler frequency that was indicative of a particle as it traversed the laser fringe pattern was proportional to its velocity, a proportionality constant or scale factor was determined by determining the components of the following expression:

$$K = \frac{\lambda}{2\sin\frac{\theta}{2}}$$

where λ is the wavelength of the laser light, $\frac{\theta}{2}$ is half of the convergence angle between the two beams, and K is the scale factor. The K was a property of the particular laser generator being used. The angle was measured by projecting the laser beams on a wall at some known distance from the focal point of the two beams. The distance between the two laser projections on the wall was measured and halved for each beam separation. This value was divided by the distance from the focal point to the wall and the inverse tangent of this result was the half-angle of the angle formed by the two beams.

Once the scale factor had been computed, the theoretical doppler frequency which corresponded to a particular particle's velocity was determined. This procedure was used to determine the expected doppler frequencies for the range of velocities attainable by using the DISA rotating disc which contained

embedded particles of the size comparable to those that would be used in the seeding process. By focusing the two beams on the disc at different radial positions, different tangential velocities were measured as the disc rotated. The disc had the property of simulating seeding particles at velocities of 10 cm/sec to 70 cm/sec.

This method was utilized to test the performance of the counter in its ability to attain the required raw data and the HP-9825 software in its ability to convert the raw data into doppler frequencies. The expected doppler frequencies for various velocities and beam separation settings were compared with the actual frequencies obtained from the output of the HP-9825. Within the accuracy of placing the beams' focal point on the desired radial position of the disc that would result in a particular velocity and of the disc rotating at its design angular velocity, the HP-9825 program output proved to be effective and accurate.

APPENDIX C

ABRASION TESTS

Prior to performing the LDV experiments involving the seeding of minute particles into the transonic compressor, the question of whether the seeded particles would have any abrasive effects on the aluminum compressor rotors needed to be examined. This was accomplished by using the blow-down free jet in the Turbine Lab at the NPGS annex with the 4-inch diameter converging nozzle attached to attain an exit flow velocity at or near a Mach number of 1. The exit flow was used to simulate the flow that could be expected at compressor rpm's high enough to create transonic flow on the rotor blades. In the wake of the jet, a polished plexiglass circular rod of 0.5 inch diameter was positioned to simulate an aluminum compressor rotor blade. A soft material such as plexiglass was used so that in the case where abrasion was detected from the tests, then the relative hardness of plexiglass and aluminum could be used to determine if any appreciable abrasion would also occur on the aluminum blade edges and surfaces.

Three thirty minute runs were completed in the following configurations: 1) a plexiglass rod positioned five inches from the nozzle exit with no seeding and no obstructions upstream, 2) a plexiglass rod seven inches from the nozzle exit with seeding added at the center of the exit flow administered by a 0.125 inch diameter metal probe extending into the exit flow,

and 3) a plexiglass rod seven inches from the nozzle exit with the metal probe in place but with no seeding applied. The results of the tests were conclusive that no observable abrasion was caused by the seeding. Some abrasion was noticed but since it was common to all three tests, it was determined that this abrasion was attributed to the flow contaminants characteristic of the blow-down free jet apparatus. It was concluded that seeding the flow ahead of the transonic compressor would not present an abrasion problem for the compressor blades.

APPENDIX D

WINDOW REFRACTION CONSIDERATIONS

Even though a plexiglass window was not used in the data acquisition phase of the experiment, its refractive effect upon the laser beams as they propagated through it was investigated. To investigate the flow velocities behind the compressor rotor section at higher rpm's than were allowed for this experiment, it would be necessary to install a window to prevent the intermixing of the compressor's internal flow characteristics and the atmospheric conditions external of the compressor casing and still maintain the ability to take flow velocity measurements. In the investigation of the practicality of using a window, a small cylindrical plexiglass window was utilized to provide the passageway to allow the laser light to enter the turbomachine and to permit the exiting of the back-scatter light signals. To be able to make accurate and useful velocity measurements, it was necessary to determine where the laser measuring volume was located within the flow field. By passing the converging laser beams through the plexiglass, the resulting refraction of the laser beams was measured. It was determined that for an estimated index of refraction of 1.50, the measuring volume should be located at a point 0.16 inch farther away from the inner casing wall.

This 0.16 inch difference was confirmed to be the actual focal length difference due to refraction by setting up the

laser apparatus with and without the window installed. Initially, the measuring volume was positioned on the hub of the compressor without the window installed. When the window was installed, the two beam spots were observed to be separated. Using the calibrated traversing mechanism the laser system was moved farther from the compressor at intervals of 0.04 inch. After each interval had been traversed, the position of the beam spots was checked. After 0.16 inch had been traversed, the beam spots were observed, as accurately as possible, to have merged into one spot thereby confirming the calculations performed previously.

REFERENCES

1. Durst, F., Melling, A. and Whitelaw, J. H., Principles and Practice of Laser Doppler Anemometry, Academic Press, Inc., New York, 1976.

2. Compact Syringe Pump Operating Instructions, Harvard Apparatus Company, Inc.

3. Type 55L77 Beam Expander Instruction Sheet, DISA Information Department.

4. Instruction Manual Model 3Ø75 Constant Output Atomizer, Thermo-systems, Inc.

5. DISA 55L90 Counter Processor Instruction Manual, DISA Information Department.

6. DISA Type 556 Laser Doppler Anemometer Mark II Instruction Manual, DISA Information Department.

7. West, J. C., Digital Programmable Timing Device for Fast Response Instrumentation in Rotating Machines, Naval Postgraduate School M.S. Thesis, June 1976.

8. Winters, K. A., Development of a Method for Measuring Velocity at the Exit of a Compressor Rotor Using Kulite Probes with Synchronized Sampling, Naval Postgraduate School M.S. Thesis, March 1978.

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